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POWDER PROCESSING OF TRIP STEEL

SAUL ISSEROW
MATERIALS APPLICATION DIVISION

April 1977

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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ABSTRACT

Prealloyed powder of a TRIP steel alloy was prepared by the rotating electrode process. The powder was consolidated to bar stock by extrusion at 1800 or 2000 F. The bar stock was rolled at 850 F to a series of reductions up to 80% with and without intermediate solutionizing. Rolled strips were evaluated in tension tests, which showed the capability of suitably processed powder to achieve the combination of high strength and ductility demonstrated in cast/wrought stock. Stock prepared by extrusion of powder at 2000 F was outstanding in strength, elongation, and reduction of area when warm rolled at 850 F directly from extrusion without intermediate solutionizing. The mechanical behavior of powder subjected to the various combinations of extrusion and solutionizing can be understood with the help of the metallographic observations. The 1800 F extrusion contains substantial precipitates, presumably carbides, which are detrimental to mechanical behavior. Solutionizing removes these carbides, providing material similar to cast/wrought stock as prepared for the warm rolling. The 2000 F extrusion has a solutionized structure, not amenable to improvement by a subsequent solutionizing anneal.

INTRODUCTION

The phenomenon of TRIP (TRansformation-Induced Plasticity) permits the achievement of an unusual combination of strength and ductility (or toughness) in steels of appropriately selected compositions.[1] These compositions must have strong austenite that is stable under service conditions (before yielding). On the other hand, this austenite has to manifest instability by transforming to martensite when strained, effectively being strain hardened.

The utility of TRIP depends on achieving the desired strength level in the austenite. Then, when plastic strain starts, the transformation to the harder martensite delays the usual necking and the gage section is able to undergo considerable elongation before failure. The local strengthening enables the steel to manifest higher values of both ultimate strength and elongation.[2] In a similar manner, the transformation can be seen as absorbing energy and thus contributing substantially to fracture toughness.[3]

The principal route for the necessary strengthening of austenite remains the heavy ausforming used in the original development of TRIP steel by Zackay et al.[1] In work on rather heavily alloyed steel, strengthening has been achieved by reductions up to 80% in prior deformation of austenite (PDA) by warm rolling at about 850 F, well above M_d (M_d being the highest temperature at which martensite formation is induced by deformation). The need for such heavy working to impart high strength severely limits both the size and the configuration of components that can be prepared from material with such an attractive combination of strength and ductility. Means have been sought to eliminate or reduce the need for PDA for strengthening of the austenite.[4,5] In the work reported here, prealloyed powder was explored as a means of reducing the amount of prior working needed for a high strength level. Such powder has led to improved mechanical behavior in other alloy systems.[6]

MATERIALS PROCESSING AND EVALUATION PROCEDURES

The rotating electrode process (REP) was applied to Zackay's A-1 TRIP composition (9Cr, 8Ni, 4Mo, 2Mn, 2Si, 0.3C) to obtain prealloyed powder with a very fine microstructure.[7] The scheme for subsequent processing of the powder is represented in Figure 1. The powder was consolidated to rectangular bar stock by hot extrusion at two temperatures. These bars were machined to strips in both

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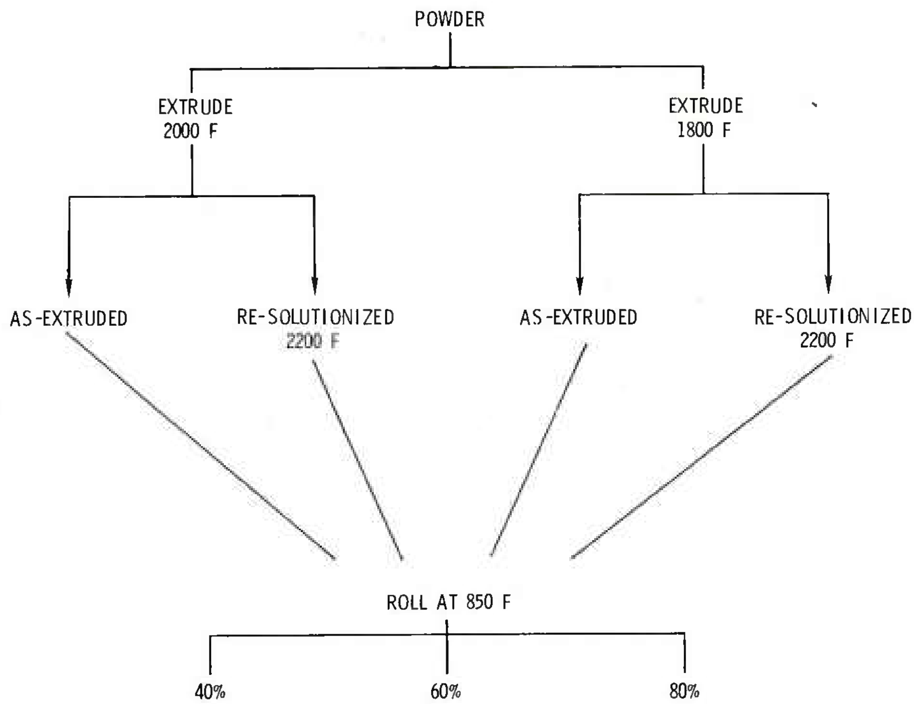


Figure 1. Processing of TRIP steel powder.

the as-extruded and re-solutionized conditions, then rolled at 850 F to thickness reductions of 40%, 60%, and 80%. Tension specimens were prepared from these rolled strips.

Powder Preparation

Six electrodes for conversion to powder were machined from four square castings that were forged at 2000 F to suitable rounds. The castings had been vacuum-induction melted. Two castings (1036 and 1037), originally weighing 25 pounds, each gave a single electrode; the other two (1050 and 1051), weighing 50 pounds, each gave two electrodes. The analyses of the castings are summarized in Table 1. Before forging, the castings were cropped generously at the top to remove the center pipe and eliminate any seams or inclusions which might contaminate the powder and subsequently impair ductility. For the same reason, each 10-in.-long electrode was machined to about 2-in. diameter or less as required to obtain a clean surface. The flat ends were checked for soundness by dye penetrant. (Magnetic inspection was not feasible for the nonmagnetic austenite.) Spherical powder was prepared by the REP and was found to have the following sieve analysis:

Sieve, U.S. series:	35	45	60	80	120	170	230	325	PAN
Sieve opening, microns:	500	354	250	177	125	88	63	44	<44
Percent retained on screen:	0	0.38	10.97	34.74	30.49	13.69	7.33	2.22	0.18

Extrusion and Warm Rolling

The powder was loaded into 5-in.-diameter cylindrical steel cans (11 gage thickness) to about 68% of theoretical density. (Immersion weighing of electrode stubs gave a density of 7.90 g/cc or 0.285 lb/cu in.) The cans were evacuated, outgassed at 800 F and sealed. Two rectangular bars were extruded in a 1400 T press at 2000 F and 1800 F to nominal dimensions of 2 in. x 1 in. The bars were water quenched immediately after extrusion. The reduction ratio R was 10:1. Additional details of the extrusions are summarized in Table 2.

Six-inch-long sections of the bars were heat treated for one hour at 2200 F and water quenched. The Rockwell hardnesses of these bars were found to be as follows:

Bar	As-Extruded	Solutionized
1 (2000 F)	HRC 20 (HRB 98)	HRB 92
2 (1800 F)	HRC 23 (HRB 100)	HRB 92

The bar stock was used to machine strips (1 in. wide, 6 in. long, and 0.18 in. or 0.5 in. thick) for rolling to a common thickness of 0.1 in. The 0.18-in. strips were rolled 40%. The 0.5-in. strips were rolled 60% to 0.2 in. thick and cut in two lengths, one of which was rolled to 0.1-in. thickness for a total reduction of 80%. Each strip was held in the 850 F furnace for at least an hour before the initial pass and reheated for 10 minutes between passes.

The changes in roll space settings and consequently in strip thickness were adjusted in accordance with the initial and final thickness. The 0.18-in. strip had the settings changed in steps of 0.020 in. (except for finishing of two strips); the thickness decreased about 0.015 in. per pass till about 0.1 in. was achieved. The 0.5-in. strip had the setting changed in steps of 0.050 in. with consequent thickness decreases of about 0.040 in. until 0.2 in. was reached. Halves of these strips were then rolled to about 0.1 in. with the settings generally changed in steps of 0.020 in., the thickness then decreasing about 60%

Table 1. ANALYSES OF CASTINGS OF TRIP STEEL

Casting	Element (Weight Percent)					
	Cr	Ni	Mo	Mn	Si	C
1036	8.92	8.18	4.07	2.10	2.02	0.31
1037	9.13	8.08	4.09	2.07	2.10	0.32
1050	9.09	8.04	4.20	2.06	2.04	0.34
1051	9.06	8.05	4.10	2.02	2.04	0.33

Table 2. CONDITIONS IN EXTRUSION OF TRIP STEEL POWDER BILLETS

Billet/Bar No.	1	2
Temperature, deg F	2000	1800
Speed, in./min	100	100
Forces		
Upset		
F, tons	1265	1320
K,* ksi	27.3	28.5
Running		
F, tons	1200	1260
K,* ksi	25.9	27.2

*K = F/A/ln R where R is reduction ratio to 80% of the setting decrease. In this final rolling sequence from 0.2 to 0.1 in., the two as-extruded strips split in one of the early passes. The bar 1 strip survived three more passes (down to about 0.13 in.) than the bar 2 strip.

Tension Testing

The flat tension specimens prepared from the rolled strips had a gage section 1 in. long and 0.250 in. wide with a 3/16-in. radius. The thickness was left as-rolled, that is 0.1 in. for 40% and 80% reductions, 0.2 in. for 60% reduction. Testing was conducted in a 20,000-pound capacity Instron testing machine at a cross-head speed of 0.04 in./min utilizing friction grips.

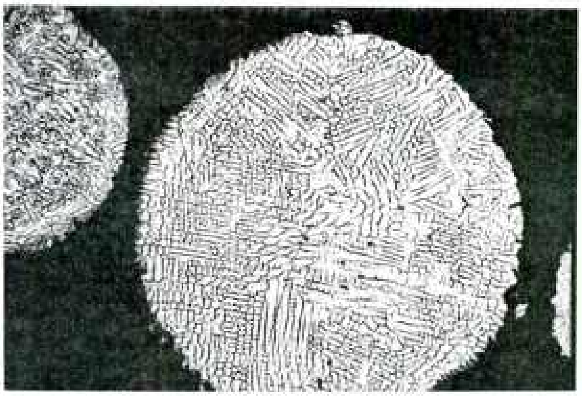
RESULTS

Microstructure

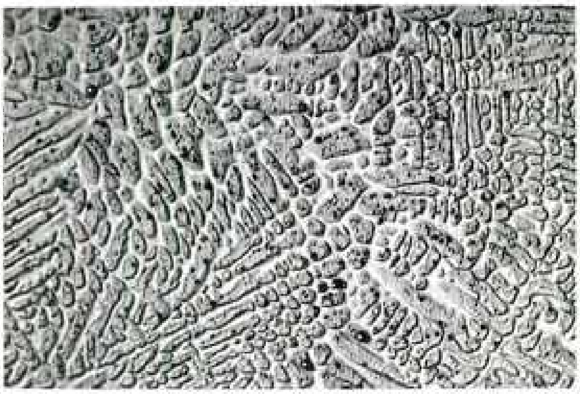
Metallographic examinations at the various stages are shown in Figures 2, 3, and 4. The etchant for all these samples was as follows: 5 g $CuCl_2$, 100 cc conc. HCl, 100 cc ethyl alcohol, 100 cc water.

The powder (Figure 2) has a very fine interdendrite spacing, estimated well below 5 microns. No other microstructural features were resolved.

The structures resulting from extrusion at the two temperatures are considerably different. The 2000 F extrusion (Figure 3a) gave a structure with no evidence of carbide precipitation and with slightly finer grains than in the usual stock solutionized at about 2200 F. The 1800 F extrusion (Figure 3c) is much finer grained and shows considerable precipitation. Solutionizing at 2200 F converted both extrusions to relatively precipitate-free material with coarse grains. The 2000 F extrusion (Figure 3b) now resembles conventional cast/wrought material after solutionizing. In contrast, the stock from the 1800 F extrusion (Figure 3d) is finer grained.

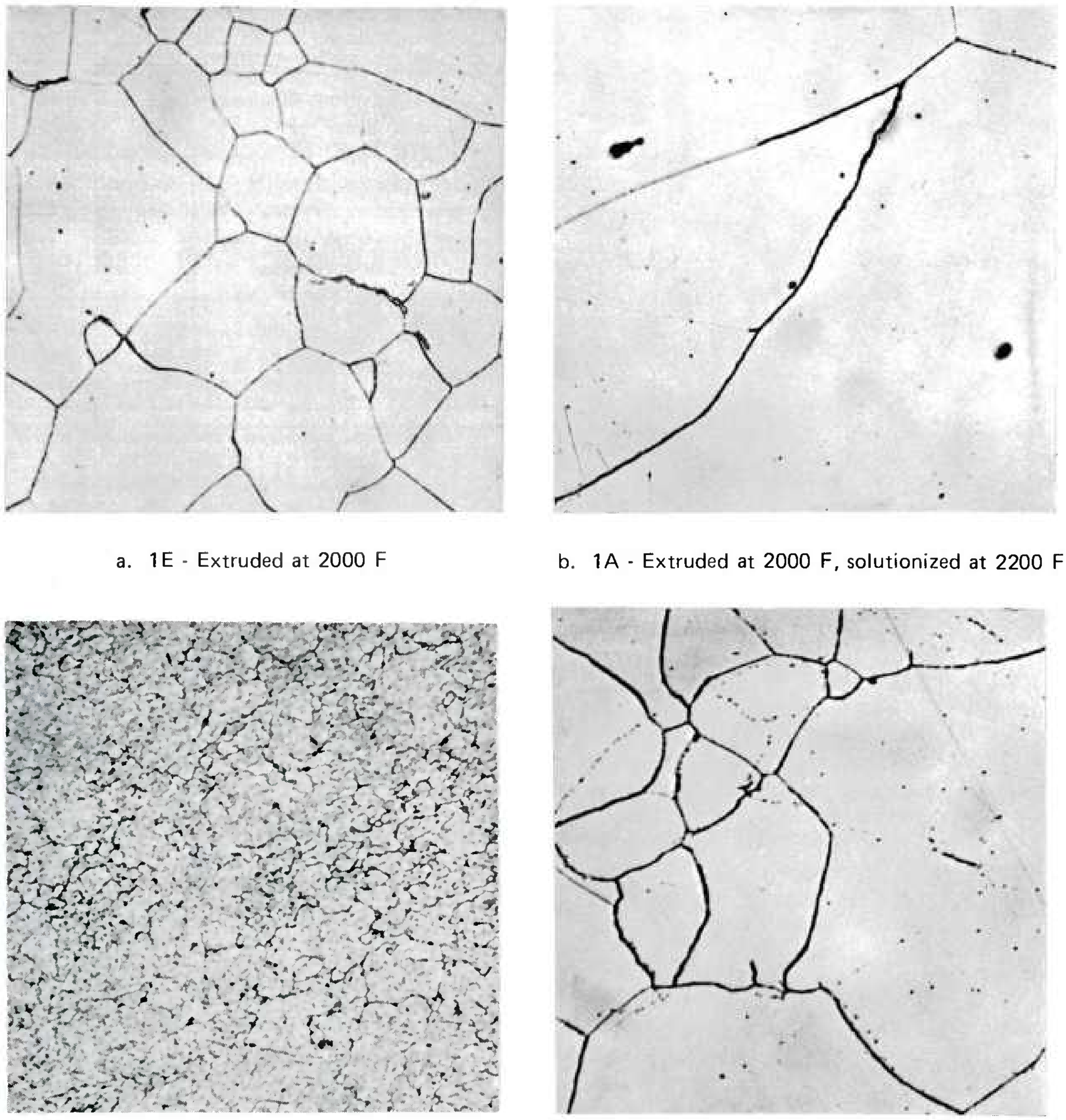


a. Mag. 250X



b. Mag. 750X

Figure 2. TRIP steel powder prepared by rotating electrode process.



a. 1E - Extruded at 2000 F

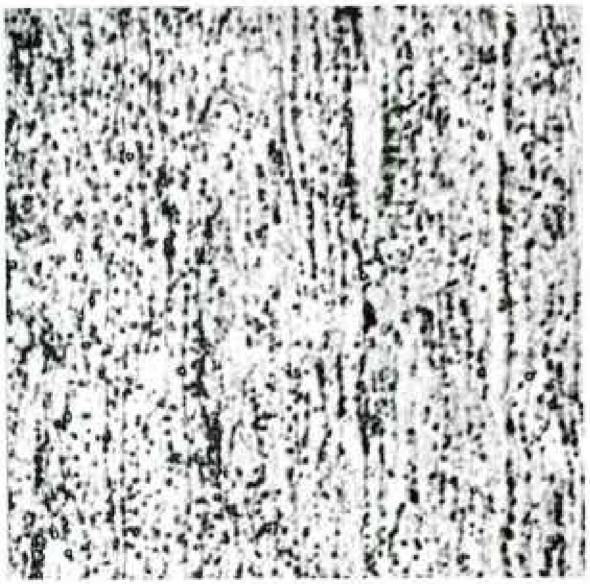
b. 1A - Extruded at 2000 F, solutionized at 2200 F

c. 2E - Extruded at 1800 F

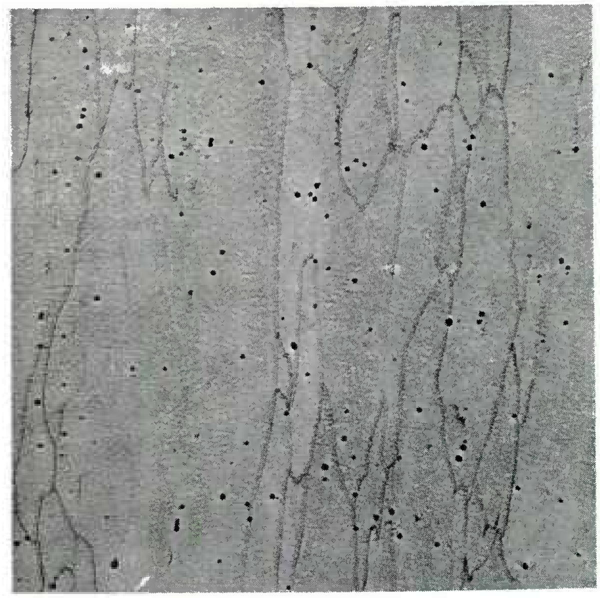
d. 2A - Extruded at 1800 F, solutionized at 2200 F

Figure 3. Extruded bars of TRIP steel. Mag. 750X
(Faces transverse to extrusion direction).

Figure 4 shows three different starting materials rolled to 60% reductions. The structures are seen to derive from those of the respective starting materials shown in Figure 3. The lower temperature extrusion, when rolled directly (Figures 4a and c), shows very fine grains and heavy precipitation. The solutionized materials (Figures 4b and d) show light precipitation with grain sizes paralleling those of their precursors.



a. 2E-B - Stock as-extruded at 1800 F. Mag. 1000X



b. 1A-B - Stock extruded at 2000 F and solutionized. Mag. 100X

c. 2E-B - Stock as-extruded at 1800 F. Mag. 100X

d. 2A-B - Stock extruded at 1800 F and solutionized. Mag. 100X

Figure 4. Strips of TRIP steel, rolled to 60% reduction at 850 F. (Faces parallel to rolling direction).

Mechanical Behavior

The results of the tension tests are summarized in Table 3. Also included are data reported by Zackay et al.[1] for two cast/wrought samples of very similar composition (their A-1). Comparison of their data with stock rolled 70% or 80%

shows that the powder-derived material can give results similar to those for the cast/wrought material. The powder-derived material, however, is sensitive to the interplay of the following factors: extrusion temperature and inclusion of a solutionizing anneal before rolling.

Powder-derived stock extruded at 1800 F showed very low elongation and reduction of area when rolled 40% or 60% (samples 2E-A and 2E-B) in the as-extruded condition. Stock extruded at 2000 F showed elongation and reduction of area over 40% when rolled 40%, 60%, or 70% (samples 1E-A, 1E-B, and 1E-C) in the as-extruded condition.

Solutionizing of the 1800 F extrusion before rolling 40% or 60% (samples 2A-A and 2A-B) increased both elongation and reduction of area substantially. Presumably the effect is the same after 80% rolling (2A-E), where no as-extruded sample was available for comparison. For the 2000 F extrusion, the 2200 F solutionizing had a slight, inconclusive effect on stock rolled about 50% or 60% (1A-B versus 1E-B) and a detrimental effect on stock rolled 70% or 80% (1A-C versus 1E-C).

Conclusions are less consistent in attempts to compare the two extrusions when each is considered in its better condition, that is, the 2000 F extrusion

Table 3. TENSION TEST DATA FOR TRIP STEEL SPECIMENS

Sample*	Extrusion Temp., deg F	Condition Before Rolling	Reduction in Rolling, %	0.2% Y.S. ksi	U.T.S. ksi	Elon., %	RA, %	Fracture Appearance	Hardness HRC
This Investigation									
1E-A	2000	as-extruded	40	159.7	189.4	42.7	55	cup-cone	46.5
2E-A	1800	as-extruded	40	172.5	197.7	2.0	17	cup-cone	49.4
2A-A	1800	solutionized	40	152.2	186.8	16.3	33	wooden	47.3
1E-B	2000	as-extruded	50	160.3	201.1	49.3	62	mixed	47.9
1A-B	2000	solutionized	60	171.4	202.6	56.0	39	wooden	48.4
2E-B	1800	as-extruded	60	180.1	217.2	0	16	cup-cone	49.9
2A-B	1800	solutionized	60	184.8	215.6	42.0	(39)	jagged cup-cone	49.3
1E-C	2000	as-extruded	70	231.2	246.7	41.0	45	wooden	53.1
1A-C	2000	solutionized	80	218.5	241.1	25.2	27	mixed	52.3
2A-C	1800	solutionized	80	214.9	242.5	39.1	33	mixed	52.5
Zackay et al.[1]									
8		solutionized	80	222	254	41			
9		solutionized	80	224	257	36			

*Code for sample designation

Digit - Extrusion Temperature (Column 2)

1 2000 F
2 1800 F

First Letter - Condition (Column 3)

E as-extruded
A solutionized (annealed at 2200 F)

Second Letter - Rolling Reduction (Column 4)

A 40%
B 50 or 60%
C 70 or 80%

as-extruded (1E) and the 1800 F extrusion solutionized (2A). In material rolled 40% or 80%, the 2000 F extrusion is equal or better in both strength and ductility. However, in material rolled 60%, the 2000 F extrusion is better in elongation but poorer in strength.

DISCUSSION

This program has demonstrated that stock from prealloyed powder can be processed to achieve the same combination of high strength and ductility as in cast/wrought stock. With both types of stock this achievement depends on imparting sufficient warm working, of the order of 80% reduction, to render the austenite amenable to the TRIP phenomenon. The program has shown the extent to which the response of the powder stock depends on the extrusion temperature and on the inclusion of a solutionizing step before the final warm working by rolling. The powder stock required about as much warm working as the cast/wrought stock for the same strength level with high ductility. Particularly intriguing is the very high reduction of area (45%) in high-strength strip obtained directly from powder extruded at 2000 F (1E-C). Individual test results can now be understood in light of the microstructures as determined by the processing history.

Powder extruded at 1800 F showed tensile properties indicating that the extrusion operation left the metal with a detrimental precipitate, presumably carbide (Figure 3c). This precipitate was removed in the solutionizing step, which restored the stock to a condition (Figure 3d) equivalent to that of cast/wrought stock solutionized for rolling. An analogous dependence of ductility on the 2200 F solutionizing was noted in the rolling at 850 F. The removal of the precipitate by the 2200 F treatment is also seen in the comparison of strips rolled 60% without (Figure 4c) and with the solutionizing (Figure 4d).

Powder extruded at 2000 F (Figure 3a) is in a solutionized condition. The post-extrusion solutionizing at 2200 F hardly improved tensile behavior and, in fact, impaired strips subjected to the high warm reduction. Any such impairment may be a consequence of grain coarsening in the 2200 F solutionizing (Figure 3b). Evidence of such coarsening is further provided by the 60% rolled stock (Figure 4b) when compared with the closest material available for comparison (Figure 4d). The high elongation and reduction of area of the 2000 F extrusion (1E-C, as-extruded) suggest that the powder can give a premium material, precipitate-free and relatively fine grained (Figure 3a). This extrusion temperature has hardly been optimized. Hence, it is conceivable that further work would define an optimum extrusion temperature preserving or producing a desirable structure from powder. In consequence, powder would be applicable to enhance properties obtainable through the TRIP phenomenon.

SUMMARY AND CONCLUSIONS

The A-1 TRIP steel composition was converted to spherical microquenched powder by the rotating electrode process (REP). This powder was consolidated to sound bar stock by extrusion at either 1800 or 2000 F. Portions of the bars were rolled at 850 F to reductions of 40%, 60%, or 80% with or without an intermediate solutionizing anneal at 2200 F. The tensile strength of rolled strips increased with this working. With suitable prior processing conditions, notably extrusion temperature and/or solutionizing, the powder-derived stock resembles cast/wrought stock in its response to warm working. Exceptions were noted as follows in the behavior of the powder-derived stock. The 1800 F extrusion in the as-extruded condition was deficient in ductility, presumably as a result of carbide precipitation, which was overcome by solutionizing between extruding and rolling. The 2000 F extrusion in the as-extruded condition was like cast/wrought stock. The high reduction of area of stock rolled 70% indicates the potential value of the powder approach for A-1 and other compositions when extruded at optimized extrusion temperature.

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Prealloyed powder of a TRIP steel alloy was prepared by the rotating electrode process. The powder was consolidated to bar stock by extrusion at 1800 or 2000 F. The bar stock was rolled to 850 F to a series of reductions up to 80% with and without intermediate solutionizing. Rolled strips were evaluated in tension tests, which showed the capability of suitably processed powder to achieve the combination of high strength and ductility demonstrated in cast/wrought stock. Stock prepared by extrusion of powder at 2000 F was outstanding in strength, elongation, and reduction of area when warm rolled at 850 F directly from extrusion without intermediate solutionizing. The mechanical behavior of powder subjected to the various combinations of extrusion and solutionizing can be understood with the help of the metallographic observations. The 1800 F extrusion contains substantial precipitates, presumably carbides, which are detrimental to mechanical behavior. Solutionizing removes these carbides, providing material similar to cast/wrought stock as prepared for the warm rolling. The 2000 F extrusion has a solutionized structure, not amenable to improvement by a subsequent solutionizing anneal.